banks, undulating bed morphology, and large roughness elements such as large woody debris) provide better aquatic habitat than simplified, channelized reaches (see Brookes 1988 for a review). It should come as no surprise that aquatic habitat is usually maximized with an unfettered, naturally migrating river channel (Ward and Stanford 1995), as these are the freshwater stream conditions with which the fish evolved.

Impacts of channelization include loss of aquatic habitat area and diversity, reduction in shading of the channel with attendant increase in water temperature, loss of riparian habitat for wildlife, specifically loss of undercut banks and overhanging vegetation, loss of pool-riffle structure, and loss of spawning habitat. These relations are visible from field observation on Deer Creek, and would probably be evident from detailed habitat mapping within channelized/leveed vs. more natural reaches of Deer Creek. One way in which channelization and levees reduce the quality of habitat in Deer Creek is by eliminating refuge from high flows: all the flow is concentrated between the levees, leading to increased shear stress in this narrow band. Not only do fish have no place to hide in such channelized/leveed reaches, but the resulting channel typically becomes simpler as well. Thus, the initial 1949 channelization project and subsequent channel clearing, gravel removal, and levee repairs (including post-1997-flood emergency work) were detrimental to aquatic habitat in Deer Creek.

Channel modifications are commonly accompanied by installation of rip-rap on banks. Rip-rapped banks lack bank overhangs, trees and roots, and other irregularities. Although the interstices of rip-rap can provide some habitat for juveniles, overall there is a loss of habitat when a natural bank is converted to rip-rap. Numerous studies have shown that rip-rapped banks support lower densities of fish (e.g., Cederholm and Koski 1977, Chapman and Knudsen 1980, Hortle and Lake 1983, Knudsen and Dilley 1987). Moreover, hardening river banks in one location typically produces a reaction elsewhere along the channel, because flows speed up, slow down, or change in direction. As a result, erosion is initiated elsewhere, and bank protection may be proposed for the new site of erosion, initiating a cycle of erosion and costly rip-rap projects, ultimately with substantial, negative, cumulative effects on aquatic habitat.

Channel maintenance for flood control has included removing accumulated gravel deposits and large woody debris. The gravel removed from the channel is important for building complexity of channel forms (e.g., point bars, riffles) and as part of the gravel delivered to the Sacramento River by Deer Creek. Large woody debris is increasingly recognized as providing important habitat in streams (Angermeier and Karr 1984, Dolloff 1986, Fausch and Northcote 1992, Fausch et al. 1995), so the loss of this wood from the system reduces habitat complexity and contributes to the rapid transmission of flow downstream.

Upstream reaches of Deer Creek most used for spawning and rearing by spring-run chinook salmon (the canyon reaches between the Lower Falls and the Ponderosa Way bridge) have remained largely unchanged since the 1930s. Farther upstream, the Deer Creek Meadows have experienced substantial erosion and channel widening and incision, which has caused the alluvial water table to drop, drying the meadow, and changing the distribution of pools, riffles, and other habitat features. The amount of sediment from the channel erosion, and from road construction, timber harvest, and landslides in the upper basin has no doubt increased in recent decades, and most of this sediment has passed downstream. However, important spring-run salmon habitats do not appear negatively affecting by excessive fine sediments at this time, implying that most of this sediment has been transported through the system during flows sufficiently high to maintain suspension.

A Systemic, Process-Based Strategy for Ecosystem Restoration of Lower Deer Creek

With an understanding of the effects of the flood control project (and its maintenance) on Deer Creek, we can see that many of the problems in Deer Creek are, in effect, symptoms of the underlying geomorphic effects of the flood control strategy. Many of the restoration actions proposed for Deer Creek can be viewed as treatments of these symptoms, rather than addressing the underlying problem. If the style of flood management were changed to set levees back, permit overbank flooding, and eliminate channel clearing, Deer Creek would, in the course of one or more floods, reestablish a more natural channel form with better habitat.

The Deer Creek Watershed conservancy is now exploring alternative flood management strategies. One concept is to let Deer Creek overflow its south bank at the same point it overflowed in 1997 (and in previous floods) and flow across a swath of the south bank floodplain (bounded along the south by set-back levees), through enlarged culverts under Highway 99, and past the town of Vina and into the Sacramento River through an enlarged China Slough. Vina, the Abbey of New Clairvaux, and other buildings on this floodplain would be protected by ring levees. This strategy would aim to manage floods rather than control them, to let Deer Creek release pressure during floods by overflowing as it has historically done, but to set back or protect vulnerable infrastructure.

Along many rivers and streams, it is too late to reestablish natural floodplain processes because intensive urbanization of the floodplain precludes its inundation, or upstream dam construction has reduced flood frequency. Fortunately, along Deer Creek, this is not the case, and a number of landowners have expressed willingness to consider periodic flooding of their agricultural lands. The Nature Conservancy and other organizations and programs could purchase easements or title to flood-vulnerable lands, compensating the landowners. Similarly, bank protection could be removed, destabilized, or not maintained, so that Deer Creek would become free to migrate across the floodplain. In the long run, this approach (of stepping back from the river and giving it a corridor in which to flood and erode) would reduce maintenance costs, in addition to improving habitat.

Because Deer Creek is a high energy channel with essentially unaltered flow and sediment yield from its watershed, it is capable of reforming its bed and banks from channelized to natural quickly, once the disturbing factors of levees and channel clearing were removed. We could expect to see substantial return to natural conditions in one large flood, as was illustrated by some of the channel changes effected by the 1997 flood.

Taking a systemic approach such as this need not preclude short-term measures such as planting riparian trees along de-vegetated channels, or even additions of spawning sized gravel to the channel, but these measures should be undertaken with the understanding that they are unlikely to be sustainable until the channel of Deer Creek can evolve to a more complex, natural form.

LIMITING FACTORS IN THE LIFE CYCLE OF SPRING-RUN AND FALL-RUN CHINOOK SALMON

SPAWNING. Gravels in Lower Deer Creek are used for spawning by fall-run chinook, despite grain sizes considered somewhat coarser than ideal. Spring -run spawning is concentrated upstream, where the gravels occur in smaller deposits. Restoration efforts in Lower Deer Creek would benefit spawning for fall-run chinook and rearing habitat for both runs. However, there may be other, less-visible, limitations on salmon at other stages of their life cycles. For example, if abundance is very low, spawning habitat may not be limiting, because even the limited spawning habitat is adequate for the depressed populations. In this case, restoration efforts directed at other parts of the life cycle may be more effective. This has probably been the case in some years of low abundance (Figure C-2). For some of these life cycle stages, ecosystem restoration seems like a logical and supportable way to proceed; for others, species- or even stock-specific actions are more likely to yield tangible results. Limitations at different stages of the life cycle are discussed below, with letters referring to Figure C-3.

FRY REARING IN RIVERS (C). In general, chinook fry tend to disperse downstream after emergence, taking up residence along edges of streams and rivers, and selecting habitat of increasing velocity as they develop (Chapman and Bjornn 1969, Lister and Genoe 1970, Reimers 1973, Healey 1991). Habitat characteristics seem to be important, particularly the availability of cover at the banks, and riprapped banks seem to provide especially poor habitat for rearing (Michny and Hampton 1984, Schaffter et al. 1983, Brusven et al. 1986). Under the assumption that these characteristics apply equally well to Deer Creek spring-run salmon, then restoration activities in both the creek and the Sacramento River should increase growth and survival of Deer Creek spring-run by an unknown amount. These improvements may include increasing the extent of meander belts, increasing riparian vegetation and woody debris, and reducing the effect of structures that impede migration and concentrate predators. Continuing to maintain Red Bluff Diversion Dam gates open will eliminate what had been believed to be an important concentration of predators.

HABITAT CONDITIONS IN THE DELTA (D). Data on conditions for juvenile salmon in the Delta is largely confined to fall-run smolts and, to a lesser extent, fry. Although many brackish estuaries provide important rearing habitat for chinook salmon (Healey 1982), spring-run races tend to rear more in rivers. Rearing of fall-run salmon in the Sacramento-San Joaquin estuary is believed to occur in freshwater regions of the Delta (Kjelson et al. 1982). Survival of migrating hatchery-reared smolts is lower if they are released in the interior Delta than if they are released on the Sacramento River, suggesting poor conditions for survival within the Delta (USFWS data). To the extent that these poor conditions are due to inadequate habitat, ecosystem-based restoration efforts may help smolt survival as well as that of fry. Too many unknown factors exist, however, to suggest large-scale restoration efforts on behalf of salmon (e.g., the extent and importance of rearing in the Delta, the characteristics of favorable habitat, and the degree to which habitat may be occupied by either salmon or their predators). This suggests that a stepwise, adaptive-management approach to this restoration be used to begin to test assumptions about how habitat in the Delta may be improved and what affect that has on key species such as salmon.

FISH PASSAGE THROUGH THE DELTA (E) Although this is included as an illustration of potential effects on salmon, improvement of fish passage through the Delta is an ecosystem-level action which should benefit other species and stocks. Most of the emphasis in the Delta has been on survival of fall-run salmon smolts passing through on their seaward migration (Newman and Rice in prep.). The principal factors affecting survival appear to be flow in the Sacramento River, salinity distribution, and Delta cross-channel gate position (Newman and Rice in prep.). If spring-run salmon respond similarly to conditions in the Delta (except that temperature should not be a factor), there may be opportunities for improving their survival. Proposals in the Central Valley Improvement Act Anadromous Fish Restoration Plan included closing the Delta Cross-Channel gates in winter, and conducting adaptive management experiments (as in the Vernalis Adaptive Management Program), manipulating flow and exports during experimental releases of tagged late-fall-run fish to represent spring-run. Additional actions that improve the effectiveness of directional cues should benefit all salmon stocks as well.

ADULT PASSAGE AND SURVIVAL (A) Adult passage into Deer Creek is probably not a limiting factor under most flow conditions. However, high temperature in the Sacramento River could result in physiological damage or exhaustion with resulting poor survival or egg viability. Because adults hold in the stream through summer, spring-run chinook may be particularly vulnerable to poaching, which may have contributed to their decline (Sato and Moyle 1989).

OCEAN CONDITIONS (E) Survival of salmon in the ocean is reduced by natural mortality (an ecosystem condition) and fishery mortality (largely a species-based condition). Natural mortality is a function of ocean conditions, out of the control of CALFED. The fraction of fall-run salmon caught (harvest fraction) has been increasing by 0.5% per year for the last 40 years to values over 70% (based on data in Mills and Fisher 1994). This value seems excessive if it applies also to spring-run salmon, given their population size. Thus an obvious management option is to reduce harvest, particularly if it can be done in a way that uses the different migratory patterns to reduce impacts on spring-run fish.

ALTERNATIVE CONCEPTUAL MODELS FOR SALMON RESTORATION IN DECISION MAKING

With these limiting factors in mind, we now illustrate the application of conceptual models to formulating ERP actions, by identifying key events in the life cycle that affect production. We first present alternative models for spring-run chinook salmon system-wide, which lead to alternative restoration approaches, depending on the relative importance of each life stage. Second, we present a conceptual model of fall-run spawning in Lower Deer Creek, which provides a basis for choosing restoration actions in Deer Creek.

EXAMPLE 1: CONCEPTUAL MODELS FOR SPRING-RUN SALMON

ALTERNATIVE POINTS IN THE LIFE CYCLE. For illustration, we have selected just two qualitatively different models of the life cycle of spring-run chinook salmon (Figure C-5). These models are briefly summarized in Table C-1. According to Model A, spring-run salmon could be restored through control of poaching in the streams and improvement of rearing habitat in the streams and river. Model B suggests restoration by improving spawning habitat and Delta rearing habitat, and reducing ocean harvest. Both models indicate a moderate improvement through reduction of mortality on passage through the Delta. Delta conditions are discussed further below.

Clearly the expected benefits due to improvements in different locations differ greatly among these and other possible alternatives. The only way to resolve these issues is through modeling of the life cycle. With a model containing the various mortality factors, their expected response to restoration actions, and the degree of uncertainty about each, one could estimate the effectiveness of various actions and how well that effectiveness is known. The principal output of such a modeling effort would be a set of constraints on the improvement to be expected from each action. The model would not need to be very complicated, and in this case a simple model would most clearly distinguish among scenarios.

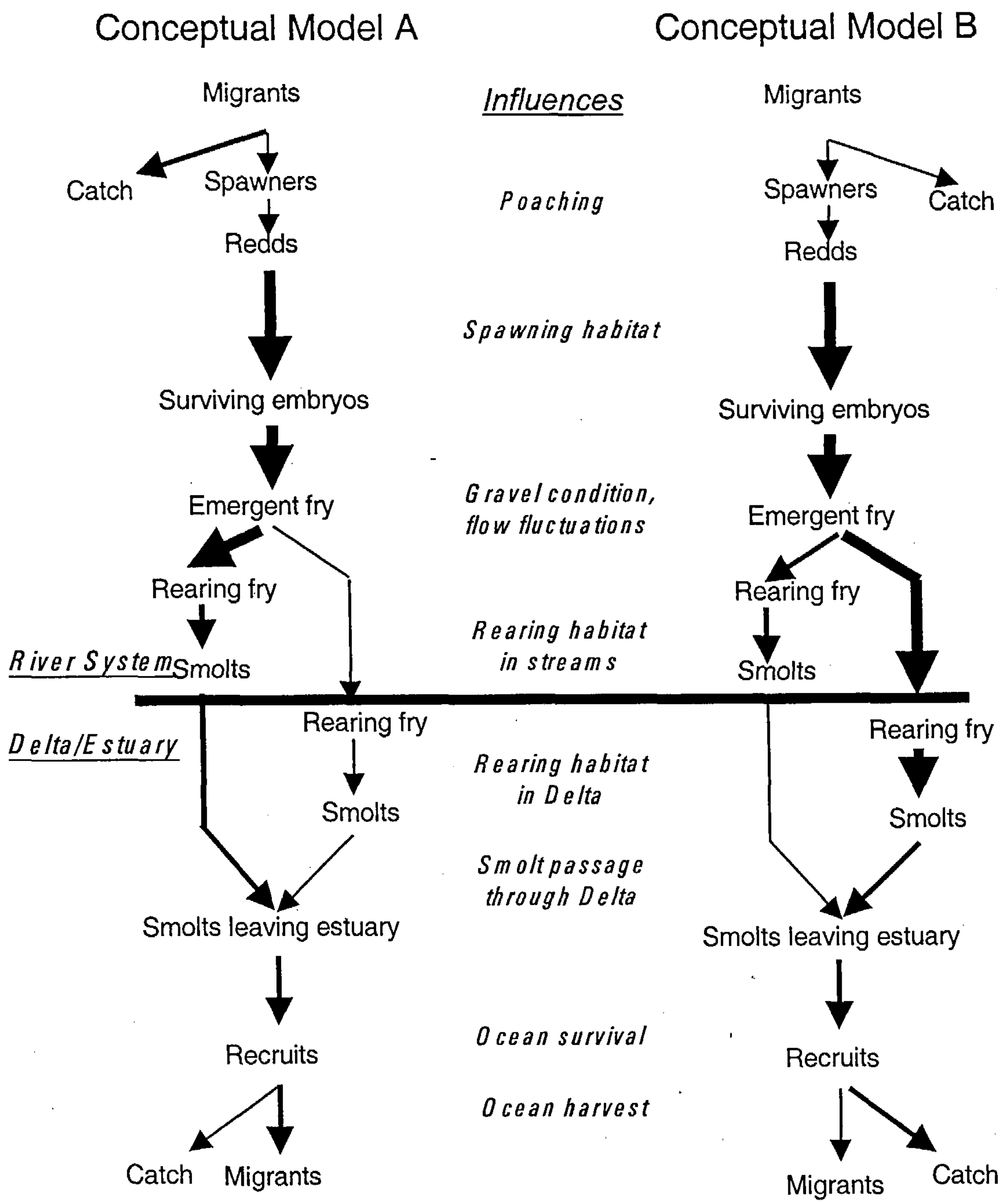
SURVIVAL IN THE DELTA. Because conditions in the Delta have received a lot of attention, and because this is the centerpiece of CALFED, we illustrate several important issues regarding survival and passage through the Delta.

Again, we use alternative conceptual models, but in this case the models differ in only one important respect: the degree of importance of tidal vs. net flows within the Delta channels (Figure C-6). Conceptual model N (for Net) holds that net flows are more important than tidal flows. According to this model, young salmon are diverted off the Sacramento River mainstem in approximate proportion to estimated net flow splits. Reverse flows such as QWEST (net flow in the lower San Joaquin River) are important either in drawing young fish toward the export pumps, or in altering salinity or other cues, confusing migrating fish as to the correct direction in which to migrate. The influence of Delta agricultural diversions (not shown in the figure) is to remove salmon in approximate proportion to the diversion flow. This model has predominated over the last few decades, despite a lack of data suggesting a strong influence of reverse flows, results of a recent study showing low abundance of salmon in agricultural diversion flows, and relatively low rates of capture of tagged salmon at the export pumps.

TABLE C-1. SUMMARY OF DIFFERENCES BETWEEN ALTERNATIVE CONCEPTUAL MODELS A AND B IN FIGURE C-5 IN RELATIVE IMPORTANCE OF VARIOUS LIFE STAGES TO POTENTIAL IMPROVEMENT IN PRODUCTION OF DEER CREEK SPRING-RUN CHINOOK SALMON.

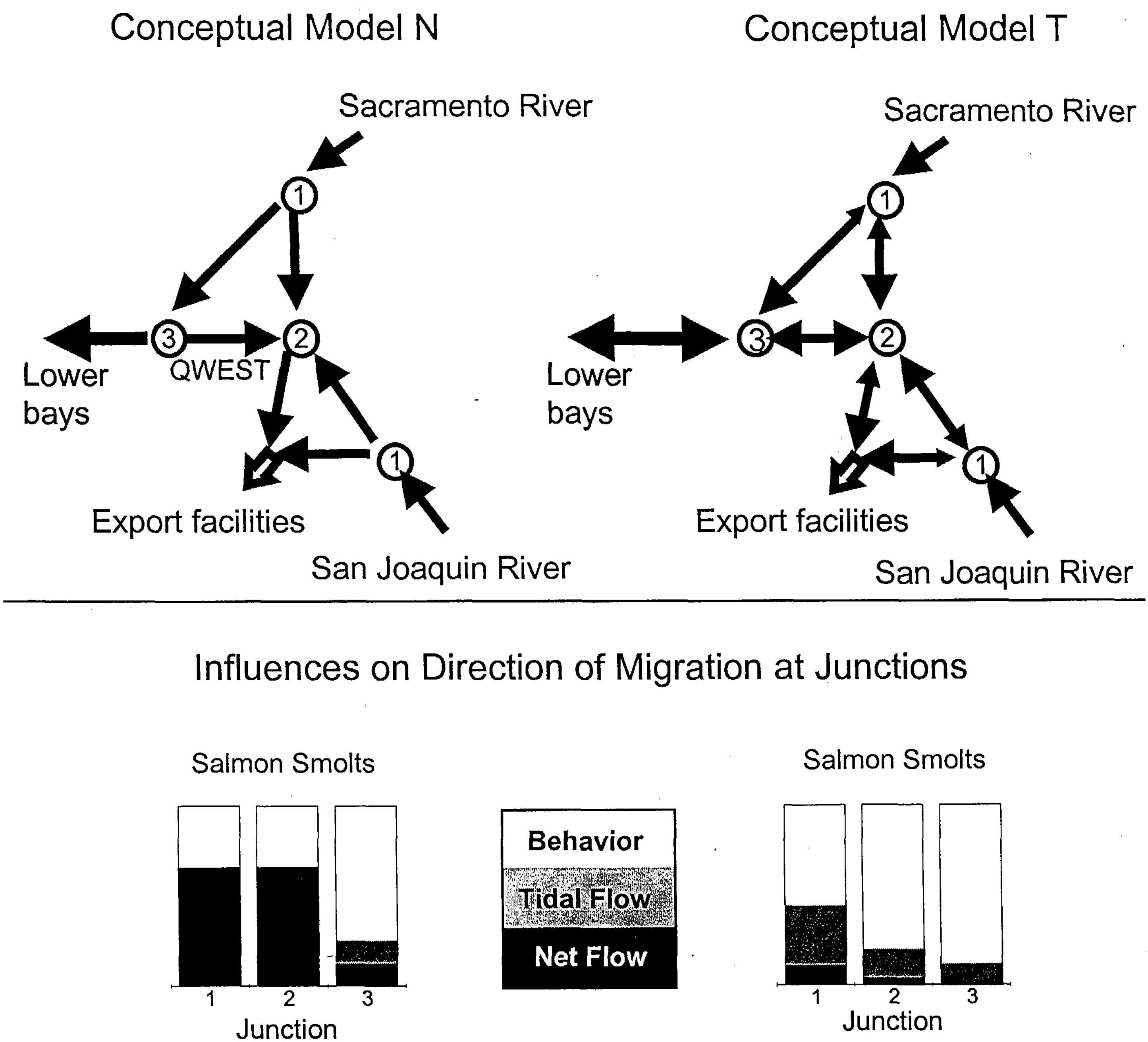
Life Stage or Event	Density-Dependent	Relative Importance	
		Model A	Model B
Poaching	Yes?	High	Low
Availability of spawning habitat	Yes	Low	High
Rearing in stream/river	No?	High	Low
Rearing in the Delta	No	Low	High
Passage through the Delta	No	Moderate	Moderate
Ocean harvest	No?	Low	High

The alternative model T (for Tides) holds that water movement is asymmetric, with dominance by ebb or flood due to net flow and tidally-driven residual flow; the further west in the Delta, and the lower the freshwater flow, the more predominant



Note: Arrows represent transformations of fish from one life stage to the next, and thickness of arrows indicates relative magnitude of population undergoing transformation. Conceptual models A and B differ in the importance of effects at several stages of the life cycle (Table C-1).

Figure C-5: Alternative Conceptual Models of Salmon Smolt Production for Deer Creek Spring-Run Chinook



Note: Arrows and circles comprise a schematic of the Delta, with the circles representing key nodes where flow and fish diverge. Single arrows indicate river inputs, and double arrows indicate flows that are partly or mostly tidal, with the sizes of the arrowheads reflecting relative flow velocities for each location. Conceptual model A depicts net flows, with arrows indicating how fish would move under the influence of these flows. Conceptual model B illustrates how water moves in response to both tides and net flow. Fish move under the influence of these flows and their own behavior. Bar charts in the bottom panel illustrate how these conceptual models differ in their prediction of the relative influence of fish behavior, tidal flow, and net flow on the proportion of fish taking alternative pathways at each of the nodes.

Figure C-6: Alternative Conceptual Models of Flow and Salmon Movement in the Delta Under Low-Flow, High-Export Conditions the tidal effects. A passive particle released in the Sacramento River has a high probability of eventually moving into Suisun Bay, a moderate probability of entering the central Delta or being entrained in Delta agricultural diversions, and a low but non-zero probability of being entrained in the pumping plants. Salmon behavior complicates this in unknown ways: e.g., splits at Delta channel junctions are a complex, at present unpredictable, function of tidal flow splits and fish behavior. Furthermore, adult salmon (and probably juveniles) use tides to assist in migration. Net flows probably have little effect except where they set up or obliterate gradients (e.g., in salinity) that may provide cues for seaward migration. QWEST and other small (relative to tidal) net flows have little or no effect, although they may be related to the environmental gradients referred to above. Finally, losses to agricultural diversions depend on the size and location, as well as the flow rate, of each diversion, and because of avoidance by fish these losses may be generally low.

In the conceptual models presented thus far, we have referred to habitat restoration in a general way, implicitly assuming that restoration projects will actually benefit salmon. However, the effectiveness of restoration projects is highly variable, depending upon the degree to which their design accounts for physical and ecological processes. In the following conceptual model, we consider in more detail the factors affecting spawning success of fall-run chinook salmon, and potential strategies for restoration.

Example 2: A Conceptual Model for Fall-Run Chinook Salmon Spawning Habitat Restoration in Lower Deer Creek

Although Deer Creek is probably most important as habitat for spring-run chinook salmon, Lower Deer Creek also provides spawning habitat for fall-run chinook (and, potentially, rearing habitat for spring-run). A number of the proposed restoration measures in Deer Creek (e.g., gravel ripping, addition of spawning gravels, installation of retaining structures) relate to spawning habitat for fall-run. Thus, an understanding of the processes and factors controlling the distribution of this habitat, and how management decisions can affect them, is important.

The conceptual model shown in Figure C-7 lays out the life stage functions involved in migration, spawning, incubation, fry emergence from gravels, and juvenile rearing. The model also discusses management and restoration actions in light of their effects on the requirements of each life stage. Under Upstream Migration, the fish must be able to swim from the ocean to their natal spawning grounds, which requires a path free of migration barriers. Barriers include dams, diversions, dewatered reaches, or reaches with high temperatures, contaminant concentrations, or low dissolved oxygen. For management, this implies that all dams and diversions below potential spawning grounds be evaluated for passage or removal, and adequate flows be provided to insure sufficient water quantity and quality to permit migration.

Under Digging Redds, the fish must be able to move the gravel, which is mostly a question of gravel size. Larger fish can move larger gravels, with the maximum size (median grain diameter) moveable being about 10 percent of the fish's body length. The sizes of gravel available is largely a function of the balance between the amount and size of gravel supplied by the watershed and local channel transport capacity. Below dams, the supply of gravel is usually reduced, so gravel may need to be added to make up for the lack of supply from upstream. In channelized and leveed reaches, the transporting power is locally increased, so gravels that might formerly have been stable are likely to be washed downstream.

Under "Incubation" in Figure C-7, the eggs must have their metabolic wastes removed and adequate dissolved oxygen, both of which depend on adequate intragravel flow past the eggs, which in turn depend on sufficient hydraulic gradient to drive the flow and sufficient permeability in the gravels to permit the flow. The hydraulic gradient depends upon the location within the longitudinal profile and local channel geometry, with the pool-riffle transition typically creating an excellent gradient for intragravel flow (water wells down into the bed at the tail of the pool, upwells from the riffle). For ecological management, this implies that undulations in the streambed are important

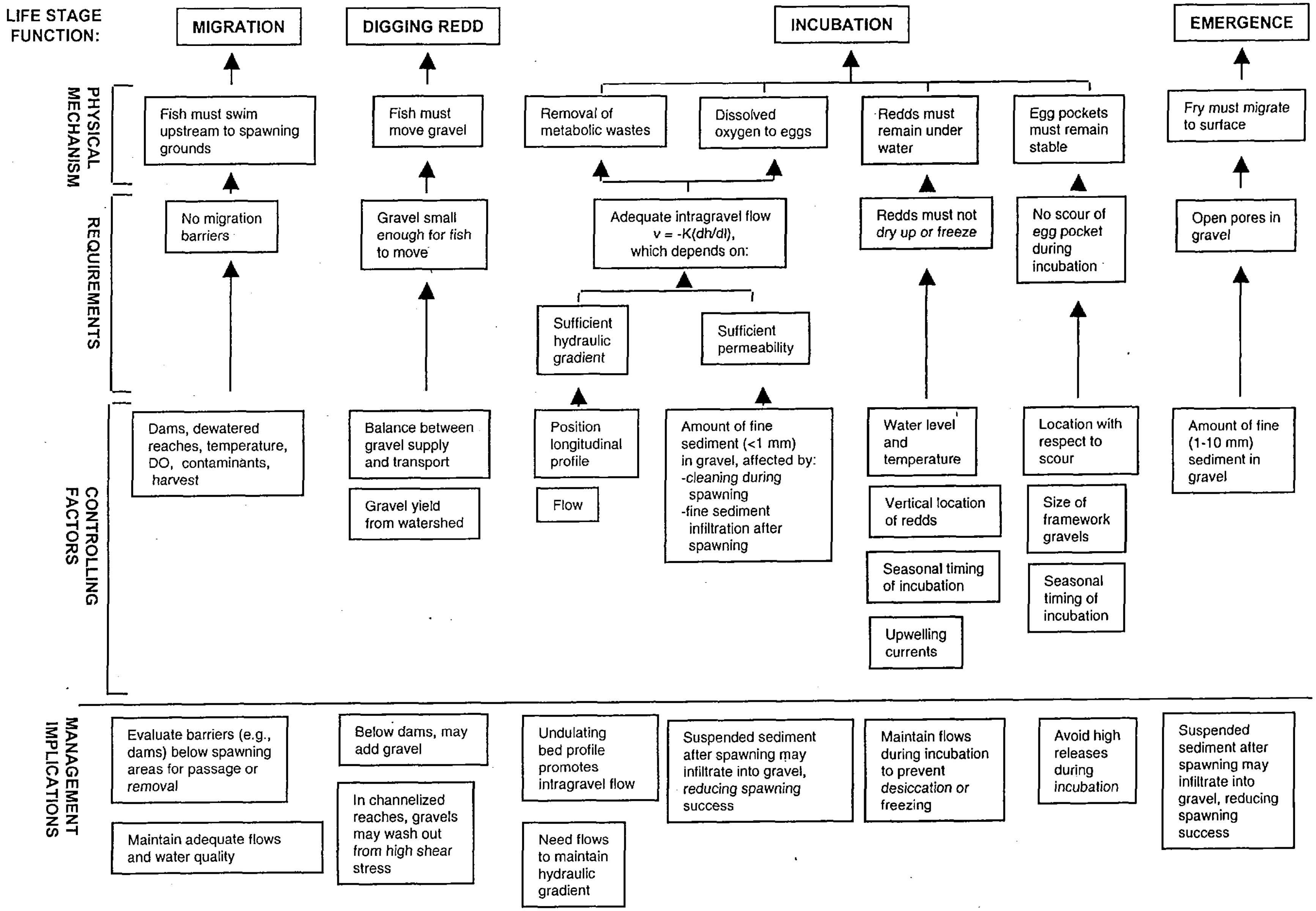


Figure C-7: Conceptual Model of Salmon Spawning, Showing Factors Affecting Success at Various Life Stages ecologically, and should be maintained. The permeability depends upon the amount of fine sediment (finer than 1 mm) in the gravel, which in turn is affected by the amount of fine sediment present before the fish spawned, the cleaning effect of the fish, and fine sediment infiltration after spawning. This implies that gravels with initially high levels of fine sediment can be improved during spawning, but subsequent high suspended sediment concentrations can be detrimental. Thus, the timing of fine sediment delivery to the channel may be as important as the amount.

Also under Incubation, redds must remain underwater, so they must be located where they do not dry up (or, in other climates, freeze). This is controlled by the streamflow (especially any drops during incubation), the location of individual redds with respect to seasonal low water levels, and the timing of incubation with respect to seasonal flows. For management this implies that adequate flows are needed during the spawning and incubation season. For successful incubation, the egg pockets of the redds must remain stable, i.e., the gravel must not be scoured (at least down to the depth of the egg pocket), because salmon eggs are vulnerable to crushing if the gravel moves. This is controlled by the location of redds in the channel with respect to bed mobility, the size of the gravel, and the timing of incubation with respect to high flows. For management, this implies that on channelized reaches with increased shear stress for a give discharge, redds are more likely to be scoured than in unchannelized, natural reaches.

Under Emergence, the fry must be able to migrate through interstices in the gravel upward to the surface, so the interstices must not be filled with fine sediment (1-10 mm). This depends on the amount of fine sediment (1-10 mm) in the gravel, which is controlled by the factors discussed above.

Under rearing, the juveniles require habitats with suitable temperatures, adequate cover, refugia from high velocity flows, and food. The habitats provided by a sinuous channel, with an undulating bed and dense riparian trees along the banks and floodplain are ideal for rearing, as they meet these requirements. For management, this implies that either the characteristics of natural, sinuous channels be artificially recreated and maintained, or that the processes which maintained those conditions be reestablished.

Implementing Adaptive Management

In adaptive management, we select actions, implement, and monitor ecosystem response. However, because our primarily target species in Deer Creek, chinook salmon, is affected by many factors besides the physical habitat we modify, we should not only monitor salmon population levels in Deer Creek and nearby drainages (which is already done). We need to monitor a suite of ecosystem responses, such as growth and survival of juvenile salmon, abundance of amphibians, abundance of native fishes, sprouting and establishment of cottonwoods.

The two spring-run chinook salmon conceptual models lead to very different choices of restoration actions. For example, Model N would suggest that moving the point of diversion might be effective in reducing losses in the Delta, and that screening agricultural diversions is an obviously effective means of improvement. By contrast, Model T implies that survival may be more a function of flow in the Sacramento River and tidal and possibly habitat conditions in the interior Delta, so that moving the point of diversion would have no measurable effect. Furthermore, agricultural diversions may have a small effect on salmon, and altering the intakes or diversion schedules to account for salmon behavior may be as effective as the far more expensive alternative of screening diversions.

The fall-run chinook spawning conceptual model illustrates the needs of different freshwater life stages of fall-run chinook salmon, and can be used to evaluate various restoration actions. For example, adding gravel to the specific sites in the channel may provide localized, short-term benefits to spawning habitat, but a more sustainable approach to increase habitat lies in re-establishing natural processes of channel migration, erosion, and deposition, overbank flooding, natural establishment of riparian vegetation, and transport of large woody debris.

The conceptual models also help to identify gaps in our understanding, and thus focused research and adaptive probing that would help resolve uncertainties to improve future management. For example, proportional entrainment of salmon in agricultural diversions and its dependence on location of intakes and timing of water withdrawal is not well understood and should be the subject of focused research before a large commitment of funds is made to expensive screening projects. Similarly, more needs to be known about spring-run adult mortality during summer, which can be approached by mark-recapture or other techniques. If mortality is significant, we should evaluate the potential magnitude of poaching, and design strategies to limit poaching if it is appreciable. In addition, the extent to which salmon, particularly spring-run, use the Delta for rearing should be investigated, and salmon passage through the Delta under winter conditions should be modeled using various alternative assumptions about behavior in response to environmental cues.

If ecosystem restoration is undertaken by setting back levees and permitting a dynamic, irregular channel to develop on Lower Deer Creek, the evolution of channel form should be carefully monitored. After each flood capable of moving bed material, the channel should be resurveyed, and the distribution of habitats inventoried from detailed aerial photographs and compared with similar information from 1939 aerial photographs as a way to measure recovery back to the favorable conditions that existed before the flood control project.

Improvements to freshwater habitat should be accompanied by reductions in ocean harvest to a level consistent with restoration, and we should monitor both harvest and total escapement of salmon to gauge success.

CONCLUSIONS

Implementing an effective restoration program will require more than developing site-specific restoration projects. It is essential that we step back and look at the big picture, and the big picture can be defined in more than one way. Conceptual models can provide a useful approach to look at the big picture. We have illustrated species-based and river-ecosystem-based conceptual models and demonstrated their use in decision making. Each kind of approach is useful, and each provides different information.

In any restoration program, the complex nature of river systems and multiple causes for declines in populations of important must be acknowledged and planned for. Because of this complexity, restoration actions may not yield the anticipated results. For example, habitat restoration measures for fall-run chinook salmon may not result in increased populations due to downstream factors such as over-harvesting, but the habitat restoration may increase populations of yellow-legged frogs. If the downstream problems are addressed, eventually salmon populations may increase as a delayed result of habitat improvements. Meanwhile, there are other benefits from habitat restoration, including, for example, hydrologic benefits from restoration of meadows in the upper watershed.

On Deer Creek, spawning and rearing habitat for spring run (in the canyon reaches) is in generally good condition. This implies that we should not undertake habitat enhancements in this reach to increase populations, but also that protection of this habitat becomes a top priority. One potential threat to spring-run habitat would be spills of hazardous materials into the creek from trucks on Highway 32 (upstream of the best spring-run habitat). In the past, diesel fuel has spilled into the creek, demonstrating the potential for more serious accidents. Restrictions on or elimination of truck traffic in hazardous materials on this highway should be considered.